Lunar Sample Return via the Interplanetary Superhighway

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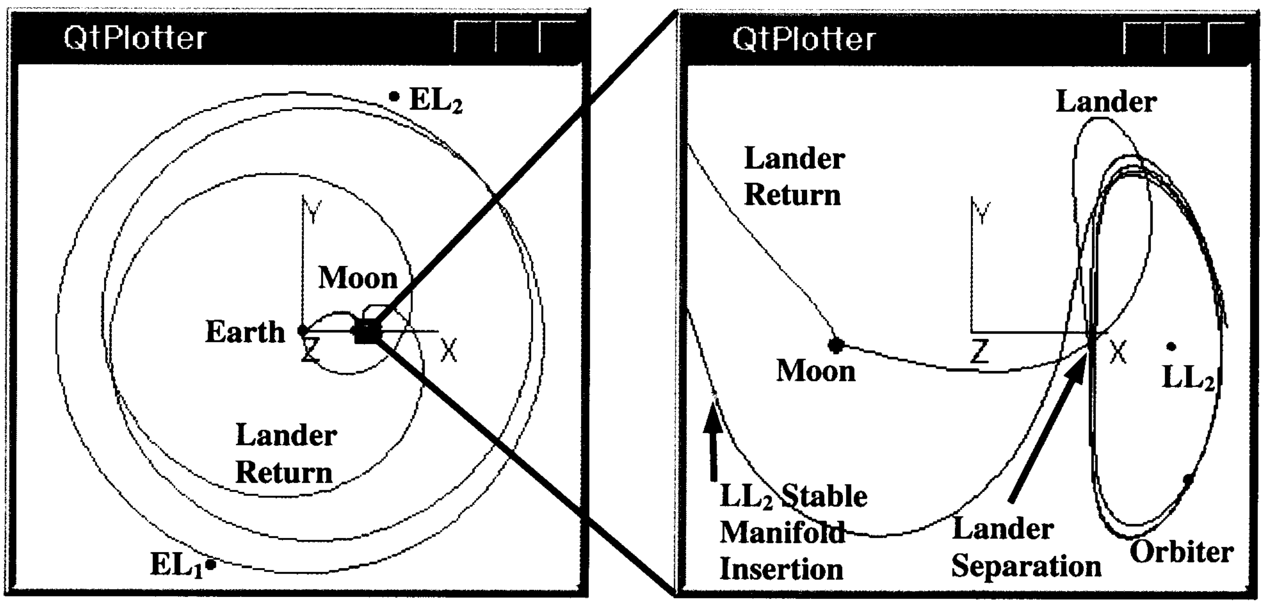

Figure 1. The whole trajectory is shown in the Earth-Moon rotating frame. The Earth launch is in brown, the insertion into LL_2 is in blue, the lander orbit to the Moon in red, and the lander return orbit is purple. The detailed plot of halo orbit about LL_2 and the landing is expanded on the right side. The purple lander return trajectory in the Earth-Moon rotating frame on the left side is not so apparent; however, in the Sun-Earth rotating frame the same trajectory appears much more sensible as shown in Figure 6 later.

ABSTRACT

The Aitken Basin at the lunar south pole is the largest impact crater known in the Solar System, piercing the Moon's mantle. A National Research Council panel recently recommended that NASA consider a robotic Lunar Sample Return mission to collect samples from the Aitken Basin and return them to Earth for study [1]. This paper describes one approach to a Lunar Sample Return mission. This Lunar Sample mission consists of two spacecraft: a communications module and a lander/sample return module; the modules are carried to the Moon by a bus. The desired landing site in this case is on the backside of Moon which cannot be seen from Earth; this is why a communications module is needed. Knowledge of the Interplanetary Superhighway tunnels and their dynamics provided good initial guess solutions for the final integrated solutions (see Figure 1). The exploration of the design trade space was facilitated by JPL's LTool2001 mission design tool.

1. INTRODUCTION

It has been decades since the last of the Moon rocks were gathered by astronauts and returned to Earth by the Apollo Program. There is now renewed interest in returning to the Moon. Where humans are involved, the roundtrip flight time must be minimized. However, in the case of a robotic sample return mission, the flight time is not as critical. It may be relaxed and lengthened to minimize the energy required to return samples from the Moon.

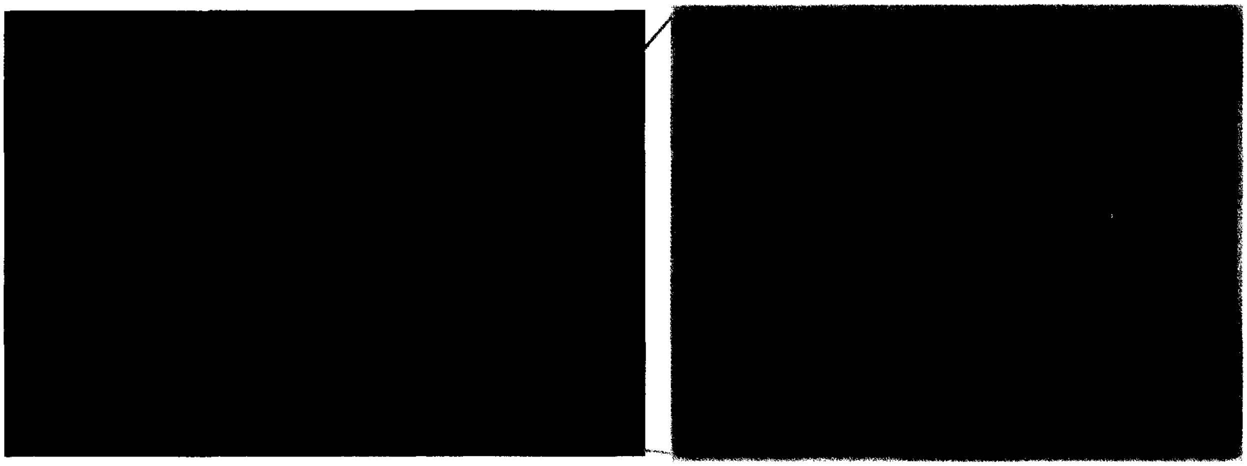

Figure 2. Artist's conception of portions of the Interplanetary Superhighway (IPS, tubes) of the Sun-Earth-Moon System generated by the halo orbits (large periodic orbits around the unstable Lagrange Points L_1, L_2, and L_3). Orbits on the blue-green tubes approach the halo orbits, while those on the red tubes go away from the halo orbits. Thus, the halo orbits are the portals, the literal "Highway Interchanges" to the Interplanetary Superhighway. The exploded view on the right is the Lunar portion of the Interplanetary Superhighway. Arrows indicate the direction of transport.

In particular, we can take our cue from comets and asteroids and exploit the low energy natural dynamics of the Interplanetary Superhighway (IPS) in the Earth's Neighborhood as shown in Figure 2. The Earth's Neighborhood is the spherical region of space around the Earth with a radius of roughly 2 million km.

2. THE IPS IN THE EARTH-MOON ENVIRONMENT

The Interplanetary Superhighway is a network of tunnels and passageways that connects various regions within the Solar System. (see Lo and Ross [2], Lo [3] for more details). It is generated by the invariant manifolds of the unstable periodic and quasiperiodic orbits within the entire Solar System modeled as a series of coupled circular restricted three body systems. In the Earth's Neighborhood, this complex web of passageways provide many interesting low-energy trajectories we used to design a Lunar Sample Return mission using libration orbits about LL_1 (Lunar L_1), LL_2, and EL_2 (Earth L_2) as shown in Figure 3 below.

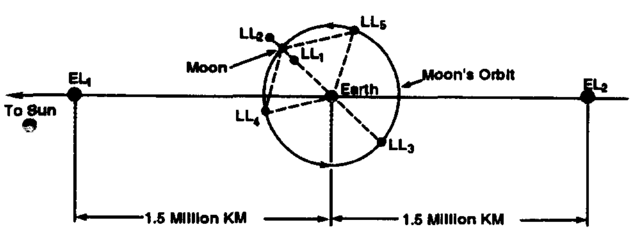

Figure 3. The Lagrange Points of the Moon ($LL_1 \ldots LL_5$) and the Earth (EL_1, EL_2) in Earth's Neighborhood in Earth rotating coordinates. The horizontal-axis containing the Sun and the Earth. Adapted from Figure 7. of Farquhar [4].

The idea of using lunar libration orbits for space missions has a long history. Colombo [5] was the first to consider it. In 1966 Farquhar [6] first proposed a "halo orbit" around LL_2 for a single communications satellite to link the Earth with the farside of the Moon (see Farquhar [4] for a more complete history). After nearly 40 years, this idea has surfaced again for the Lunar Sample Return mission.

MISSION DESCRIPTION

The Lunar Sample Return mission consists of two spacecraft: a communications module and a lander/sample return module, carried to the Moon by a single bus spacecraft. When the bus reaches the Moon, the two modules separate from the bus. Several different scenarios are studied and described below. The landing site in this case is at 180 deg. longitude, -57 deg. Latitude in the Aitken Basin, the largest known crater in the Solar System. This is on the backside of Moon so a separate spacecraft module is required for communications with Earth. We exploit the heteroclinic dynamics that connect the LL_1 and LL_2 regions to provide flexibility in various design options which were used. This is the same dynamics used to design the Earth return trajectory of the Genesis mission which just launched in August 8, 2002 (see Lo et al. [7], and Howell, Barden, Wilson, Lo [8]). Knowledge of the IPS tunnels and their dynamics provides a quick modular approach to designing libration missions. It also supplies good initial guess solutions for obtaining the more accurate integrated solutions. The exploration of the design trade space was facilitated by JPL's LTool2001 mission design tool.

MISSION DESIGN WITH IPS SEGMENTS

In this paper, we describe several scenarios for a Lunar Sample Return mission using the tubes of the Interplanetary Superhighway in the Earth's Neighborhood provided by dynamical systems theory. An excellent exposition the application of dynamical systems theory for halo orbit misisons is given by Gomez et al. [8]. The trajectory segments within the Interplanetary Superhighway in the Earth's Neighborhood provide some of the lowest energy pathways within the Earth-Moon system. Thus, libration orbits play a much greater role than as venues for solar and astrophysical space observatories. They are the generators of and the portals to this vast system of low energy trajectories.

One of the key setbacks for mission design in the libration regime has been the loss of orbital elements. Since libration orbits are nonlinear trajectories in the three body problem, the Jacobi constant is the only "integral" available and then only in the Restricted Three Body Problem formulation. This means one is unable to characterize libration orbits by parameters such as semimajor axis, eccentricity, inclination, etc. as one can for conic orbits, since orbital elements are "integral" quantities in the two body problem. In its place, the knowledge of the location of libration orbits in space and their associated invariant manifold tubes provide "replacement structures" for handling mission design using libration orbits.

Our knowledge of the libration orbit design space has advanced to the point where some rudimentary standard orbital segments may be easily constructed and used in 'tinker-toy' fashion to provide a modular approach to designing such missions. Some of these standard components are halo orbits around L_1 and L_2, orbits connecting halo orbits between L_1 and L_2, tubes leaving the planet to approach the halo orbit, tubes leaving the halo orbit to approach the planet, tubes leaving the halo orbit to escape the planet, tubes from one of the planet intersecting the tubes of another planet or satellite (see [10] and [11] for examples). These basic components can be combined with traditional planetary flybys and low thrust segments to further expand the mission design space. For the basic 'libration components' listed above, estimates of time and energy requirements are available in some instances (such as in the case of the Earth's Neighborhood) to provide quick back of the envelope estimates such as was possible with conic orbits. Thus, a mission designer can quickly string these libration components together to provide a preliminary mission design. This design can then be validated using tools like LTool where the components may be integrated using a more accurate model of the Solar System.

This approach allows the designer to select the orbital components in the mission design prior to the trajectory optimization process. As we understand more about the design process outlined above, with the help of additional theoretical understanding and empirical data on the Interplanetary Superhighway, automation and faster algorithms may be achieved through this approach.

3. MISSION SCENARIOS

The following describes three different mission scenarios using libration point orbits: transfer via LL_2, LL_1, and EL_1. A conic orbit around the moon is also considered for comparison. We will refer to these scenarios as the LL_2 Case, the LL_1 Case, and EL_1 Case in this paper.

THE LL_2 CASE: GOING DIRECTLY TO LL_2

In the LL_2 Case, the bus (with the lander and communications orbiter) is transferred to an LL_2 lissajous orbit directly via a heteroclinic connection on the stable manifold of the LL_2 Lissajous orbit. The lander is separated from the orbiter at the separation point. The sample is returned to earth via EL_2 to reduce the ΔV required. The performance is summarized in Table 1. In this case, all trajectory segments have been differentially corrected to produce an integrated end-to-end trajectory.

LL_2 Case Mission Sequence	Date (2009)	Flight Time (days)	Bus ΔV (m/s)	Lander ΔV (m/s)	Orbiter ΔV (m/s)
Translunar Injection	6/14	0	3122		
Manifold Insertion	6/18	4	570		
L_2 Halo Arrival	6/25				
Lander L_2 Departure	7/7	23		35	
Lander Landing	7/17	33		2335	
Lander Liftoff	7/28	44		2424	
Earth Return	10/16	124			
Determin. ΔV Total			3692	4794	0
Nav. ΔV Estimate			25	50	25
TOTAL			3717	4844	25

Table 1. Case LL_2 performance. Direct transfer to LL_2 Lissajous orbit with sample return via EL_2. ΔV

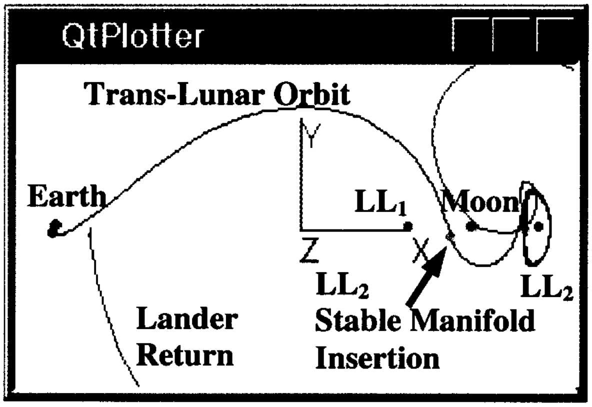

Figure 4. The trans-lunar orbit in the Earth-Moon rotating frame is shown in brown. The plot is centered at LL_2 to make the Lissajous orbit appear nicely. In this plot the lander returns to where the earth will be at its return date.

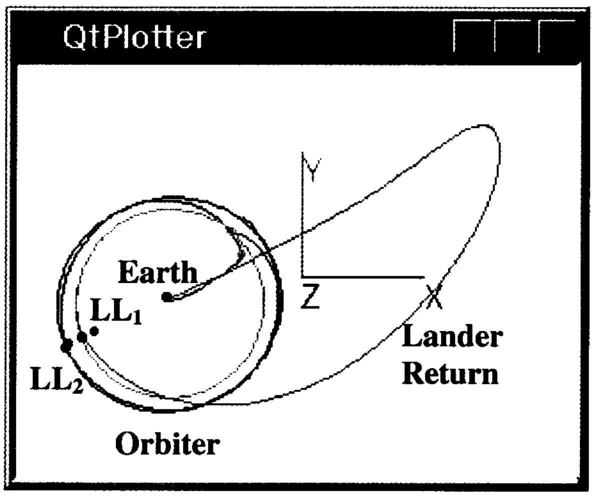

Figure 5. The entire trajectory is displayed in an inertial frame, centered at earth. The earth launch leg is in brown, LL_2 Lissajous in blue, the lander insertion in red, and the lander return in purple. The moon's orbit is in gray. LL_1 and LL_2 are snapshots at the lander return lift-off time, they move counterclockwise with respect to earth. Note that LL_2 Lissajous orbit in blue does not appear meaningful in this frame. Also note that the lander return leg in purple does not appear as a conic with respect to the earth in this frame.

The trans-lunar injection is assumed to be from a Shuttle-like (200-km altitude, 28.5-degree inclination, circular) orbit. The Bus is launched on June 14, 2009 with 3122 m/s. See Figure 4 for the trans-lunar orbit; see Figure 1 for the rest of the discussion in this paragraph. It is inserted into a point on a heteroclinc connection from LL_1 to LL_2 or a stable manifold of an LL_2 Lissajous on June 18, 2009 with 570 m/s. This ΔV

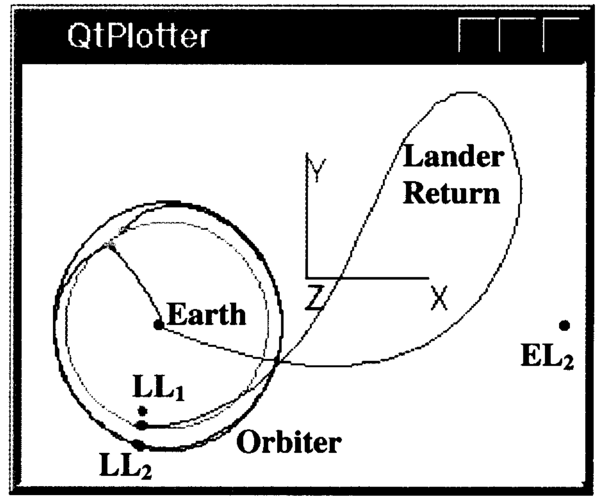

Figure 6. The entire trajectoriy is displayed in Sun-Earth rotating frame, centered at earth. The color scheme is similar. In this frame the LL_2 Lissajous orbit in blue is not apparent. However, the lander return trajectory is more meaningful; it comes close to making a Lissajous orbit around EL_2. LL_1 and LL_2 move counterclockwise about the earth.

places the bus in an LL_2 lissajous orbit approximately on June 25, 2009. The lander is separated from the communications orbiter on July 7, 2009, with 35 m/s at the closest point from the moon when it crosses near the Y-zero point. See Figure 1 for the lander separation point. The lander lands on the far side of the moon (180-degree longitude and -57 degrees latitude) on July 17, 2009, with a deceleration of 2335 m/s. See Figure 1 for the lander orbit. After the sample collection, it lifts off from the moon in the direction of EL_2 on July 28, 2009 with 2424 m/s. See Figure 5 (inertial frame), Figure 1 (Earth-Moon rotating frame), and Figure 6 (Sun-Earth rotating frame) for the complete lander return trajectory in different frames. Note that the plot is the most apparent in the Sun-Earth rotating frame as in Figure 6. It returns to the earth on November 7, 2009. The communications orbiter continues its Lissajous orbit around LL_2 until end of operations.

LL_1 CASE

In the LL_1 Case, the bus is launched onto a point in any stable manifold trajectory of the LL_1 Lissajous orbit. Then, the orbiter is transferred to the LL2 Lissajous orbit via a heteroclinic connection. The lander is inserted to the landing site on the moon. See to Figure 7 for various trajectories on the LL_1 stable manifold. The trajectories in this case have not been differentially corrected. Thus, the ΔV's and dates represented in the Table 2 are estimates.

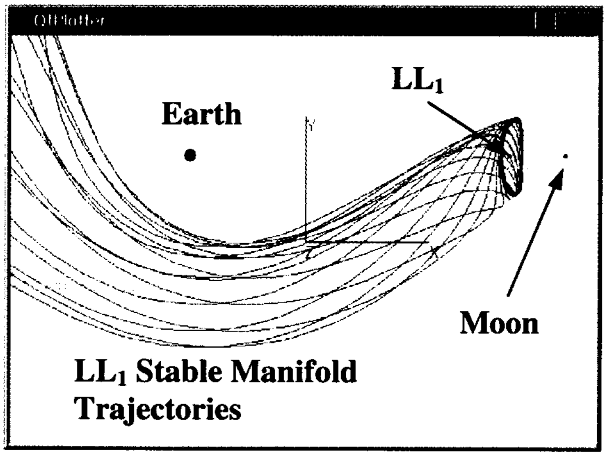

Figure 7. LL_1 stable manifold trajectories in dark green are displayed in the Earth-Moon rotating frame, centered at LL_1. The LL_1 Lissajous orbit is in brown.

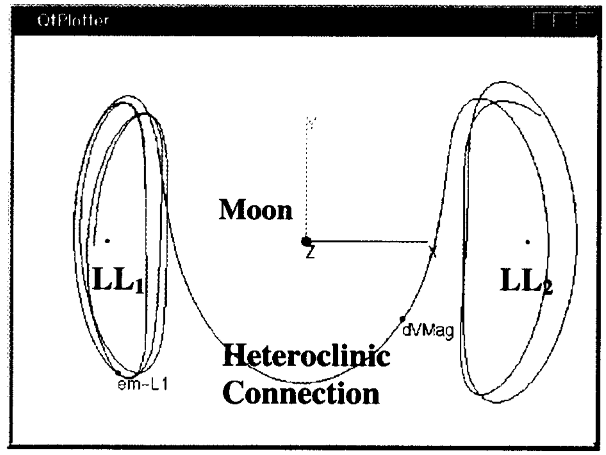

Figure 8. A heteroclinic connction on the stable manifold of the LL_2 Lissajousorbit is generated from LL_1 Lissajous to LL_2 in the Earth-Moon rotating frame, centered at the moon. The Lissajous orbits appear a bit scattered due to the eccentricity of the Moon's orbit.

LL_1 Case Mission Sequence	Date (2009)	Flight Time (days)	Bus ΔV (m/s)	Lander ΔV (m/s)	Orbiter ΔV (m/s)
Translunar Injection	6/9	0	3100		
L_1 Halo Insertion	6/14	5	600		
Orbiter Depart To L_1	6/19	10			14
Orbiter L_2 Insertion	7/7	28			0
Lander L_1 Departure	7/10	31		50	
Lander Landing	7/16	37		2350	
Lander Liftoff	7/28	49		2424	
Earth Return	10/16	129			
Determin. ΔV Total			3700	4824	14
Nav ΔV Estimate			25	50	25
TOTAL			3725	4874	39

Table 2. Case LL_1 performance. The bus is sent to LL_1 Lissajous orbit. The ΔV values are estimated.

The estimated trans-lunar injection is on June 9, 2009, with 3100 m/s. It is inserted into a point on a stable manifold on June 14, 2009 with approximately 600 m/s. This ΔV inserts the bus into an LL_1 Lissajous orbit. First, the communications orbiter is separated from the lander to the LL_2 Lissajous orbit. A small ΔV on the order of 10 m/s at the XZ-plane crossing point closest to the earth places the spacecraft to the LL_2 Lissajous orbit via a heteroclinic connection. Figure 8 shows a heteroclinic connection orbit.

One rev after the communications orbiter separation, the lander is sent on its way to the moon approximately on July 10, 2009. An estimated 50 m/s places the lander on the moon. The touch down deceleration is approximately 2350 m/s. The rest of the mission scenario is similar to the LL_2 Case.

EL_1 CASE

In order to lower the cost of ΔV to reach the LL_2 Lissajous orbit, an EL_1 Lissajous may be used. The resulting orbit is quite similar to the Genesis orbit in its starting phase. The transfer trajectory injection ΔV is 3193 m/s. The EL_1 Lissajous insertion is 60 m/s. The duration between the injection and the EL_1 insertion is approximately 91 days. This insertion nearly automatically leads the spacecraft to the LL_2 Lissajous in approximately 300 days later. The insertion into LL_2 Lissajous is approximately 13 m/s. The rest of the mission scenario is exactly the same as LL_2 direct case.

CONIC CASE

The Conic Case (Williams [12]) assumes the trajectory for the mission consists of conic arcs which are patched together. No further refinement is performed. This provides a fast estimate of the mission performance and a comparison with the low-energy missions. The bus is sent directly to the orbit around the moon on July 16, 2009, with 3100 m/s. One day later the lander and the orbiter are separated. The communications orbiter goes on an elliptic orbit with periapse facing the far side of the moon on July 20, 2009, using 481 m/s. The lander is inserted into a 100-km circular orbit on July 20, 2009, using 979 m/s. The lander is then sent to lunar surface using 23 m/s. The lander deceleration is 1703 m/s. After collecting samples, the lander/return module lifts off on August 3, 2009, with approximately 3220 m/s for a direct return to earth on August 8, 2009.

MISSION PERFORMANCE

The mission performance for each of the cases considered above is summarized and compared in Table 3. The ΔV performance of the bus, lander, communications orbiter, and their combined sum are listed individually for each case. The Total Time is the total elapsed time for the mission.

Case	Bus ΔV (m/s)	Lander ΔV (m/s)	Orbiter ΔV (m/s)	Total ΔV (m/s)	Total Time (days)
LL_2	3717	4844	25	8586	124
LL_1	3725	4874	39	8638	129
EL_1	3266	4844	25	8135	504
Conic	3100	5925	481	9506	23

Table 3. This table summarizes performance of the bus, the lander, and the communications orbiter. The Conic Case and the EL_2 Case are added for comparison.

Note that, since LL_2 Lissajous orbit is always facing the far side of the moon, the lander is always in view of the communications orbiter for all libration orbits we considered. This is an advantage over the conic trajectory around the moon. The ΔV savings is not as apparent for sending the spacecraft via either LL_1 or LL_2 Lissajous orbit in comparison to the conic estimate; however, there is a considerable ΔV saving of more than 400 m/s in sending the combined spacecraft via EL_1 than via either LL_1 or LL_2. There is also a considerable ΔV saving by returning to earth via EL_2 rather than returning directly. The ΔV for returning via EL_2 is 2424 m/s. The Soviet's Lunar series used approximately 2.7 km/s to return to earth directly from the near side of the moon (Sweetser [13]). There is a saving of 276 m/s. Besides, it is not apparent whether there can be a direct transfer trajectory with only a single lift from the far side of the moon to earth. The conservative estimate of 3220 m/s was obtained by adding the moon's hyperbolic escape velocity and the conic return trajectory to earth (Williams, [12]).

4. CONCLUSIONS

We described two scenarios for a Lunar Sample Return mission using the tubes of the Interplanetary Superhighway in the Earth's Neighborhood provided by dynamical systems theory. The trajectory segments within the Interplanetary Superhighway in the Earth's Neighborhood provide some of the lowest energy pathways within the Earth-Moon system. The Interplanetary Superhighway provided a modular approach to mission design in libration space. The resulting missions require less propulsion than a mission using standard conic arcs only for its trajectory design. In general, however, the use of the low-energy Interplanetary Superhighway requires longer travel time than conventional high-energy hyperbolic transfers. Finally, LTool was able to provide a fully integrated trajectory whereas, within the same time, the standard conic-based trajectory tools could not respond as quickly.

The Interplanetary Superhighway requires development, just as any other natural resource must be developed in order to be fully utilized. One of the key areas for further study is the role of continuous thrust in this regime. Preliminary work has demonstrated that there is a close connection between low-thrust trajectories and those within the Interplanetary Superhighway. The most obvious examples are cometary orbits which are 'continuous-thrust' objects in space that follow the Interplanetary Superhighway (see Howell, Marchard, and Lo [14]). Another area where development is needed is to understand the relation between the libration regime with conic regimes, particularly hyperbolic flybys. Finally, the Interplanetary Superhighway itself needs to be mapped, and additional tools need to be developed to explore its structure in order to provide new algorithms and orbits for mission design in this rich regime.

ACKNOWLEDGEMENTS

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